Crustal Uplift in the Southcentral Alaska Subduction Zone: A New Analysis and Interpretation of Tide Gauge Observations

Steven C. Cohen[1] and Jeffrey T. Freymueller[2]

Popular Summary:
A tide gauge measures the ocean height relative to a land datum; therefore, changes in apparent sea level height can be of either crustal or oceanic origin. Because the rates of crustal uplift at seismically active tectonic plate boundaries are often more rapid than sea level changes, measurements at appropriately located tide gauges provide insight into crustal deformation processes. We have examined the tide gauge records at the seven sites in south-central Alaska that were affected by the massive (magnitude 9) 1964 Prince William Sound, AK earthquake. We have used these records to determine the rate of postseismic (after the earthquake) crustal uplift and have compared the long term tidal gauge rates with more recent GPS rates at nearby sites. Our analysis indicates the following:

(1) The ongoing pattern of vertical motion mirrors to some extent the coseismic (earthquake) motion in the sites that subsided during the earthquake are now moving up and visa-versa. In detail, however, the correlation between the amount of coseismic motion and the current rate of uplift is poor.

(2) At Kodiak there is a distinct decrease in the rate of crustal uplift with time since the earthquake. There is also a mathematically significant change in the rate of vertical motion at Valdez and Cordova, although the behavior at Valdez, in particular, is somewhat ambiguous.

(3) On the western side of the Kenai Peninsula, i.e. at Seldovia and Nikiski the uplift rate is quite rapid, ~1 cm/yr. Such a rapid uplift cannot be maintained over the several hundred year recurrence interval between great earthquake; however, it is consistent with the "anomalous" southeast motion of GPS sites on the western side of the Kenai Peninsula that we have previously reported.

(4) Vertical motion at some other sites is consistent with strain accumulation at a plate boundary. In particular, the vertical motion at Seward, on the eastern side of the Kenai Peninsula, is consistent with our interpretation of the horizontal GPS velocities in terms of strain accumulation due to steady-state plate convergence.

[1] *Geodynamics Branch, NASA's Goddard Space Flight Center*
[2] *Geophysical Institute, University of Alaska, Fairbanks*

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Steven C. Cohen[1] and Jeffrey T. Freymueller[2]

[1] *Geodynamics Branch, Goddard Space Flight Center, Greenbelt, MD 20771*

(phone: 301-614-6466; FAX: 301-614-6522; email: scohen @carnoustie.gsfc.nasa.gov)

[2] *Geophysical Institute, University of Alaska, Fairbanks, AK 99709*

Abstract

We have examined the sea level height tide records at seven tide gauge sites in the region of southcentral Alaska that were affected by the 1964 Prince William Sound earthquake to determine the history of crustal uplift subsequent to the earthquake. There is considerable variation in the behavior depending on the location of the site relative to the 1964 rupture. At Seward, on the eastern side of the Kenai Peninsula we find a slow uplift that is consistent with elastic strain accumulation while at Seldovia and Nikiski on the western side of the Kenai we find a persistent rapid uplift of about 1 cm/yr that most likely represents a long term transient response to the earthquake, but which cannot be sustained over the expected recurrence interval for a great earthquake of several hundred years. Further to the southwest, at Kodiak, we find evidence that the rate of uplift, which is still several mm/yr, has slowed significantly over the past three and a half decades. To the east of the Kenai Peninsula we find subsidence at Cordova and an uncertain behavior at Valdez. At both of these sites there is a mathematically significant time-dependence to the uplift behavior, but the data confirming this time dependence are not as convincing as at Kodiak. At

Anchorage, to the north there is little evidence of vertical motion since the earthquake. We compare these long term tide gauge records to recent GPS observations. In general there is reasonable consistency except at Anchorage and Cordova where the GPS measurement indicate somewhat more rapid uplift and subsidence, respectively.

Introduction

Among the several geodetic data sets that have been studied in the aftermath of the 1964 Prince William Sound, AK earthquake ($M_w \sim 9.2$), tide gauge observations provide the most continuous record of ongoing postseismic and interseismic crustal movement. *Brown et al.* [1977] were the first researchers to exploit these data to extract postseismic uplift rates. They analyzed records up to 10 yrs long collected after the earthquake at permanent tide gauge sites located at Anchorage, Seward, Seldovia, Kodiak (St. Paul Harbor), and Cordova (Figure 1). Their analysis showed that postseismic uplift occurred at the first 4 sites, but subsidence occurred at Cordova. The spatial pattern of postseismic motion partially mirrored the coseismic motion in that sites that subsided during the earthquake showed uplift thereafter and visa-versa. In detail, however, the correlation between the magnitude of the coseismic motion and the magnitude of postseismic uplift rate was weak. The absolute value of the inferred rates at all sites exceeded 10 mm/yr, with a maximum uplift rate of 88 ± 38 mm/yr at Kodiak and a minimum of -12 ± 2 mm/yr at Cordova, speeds that cannot be sustained over the entire earthquake cycle of hundreds of years. *Savage and Plafker* [1991], herein referred to as *SP*91, re-examined the tide gauge observations at these locations and others with a data set that was of longer duration (through 1988). In general they found slower (sometimes considerably slower) rates of vertical motion than did *Brown et al.* [1977], although they did not report any temporal variation in the uplift rates except to distinguish between rates derived from the entire data set and from data subsequent to 1973 (i.e. ~9 years after the earthquake). The rates derived using only the post-1973 data were found to be slightly slower. At least two factors make a compelling argument for re-examining the tide gauge record at this time. First, a decade has passed since the *SP*91 analysis. Having data spanning another ten

years is important because only 35 years has passed since the earthquake occurred and the rates deduced from annual sea level determinations are subject to both year-to-year and several-year-long fluctuations due to non-tectonic processes. As the data presented in this paper indicates, the record is now sufficiently robust to determine both average uplift rates for the elapsed postseismic period and (at some sites) temporal variations. Second, contemporary GPS data are becoming available at sites located near to the tide gauge locales and provide a complementary set of observations for comparing short term to long term vertical movements.

Data Analysis

We extracted monthly mean sea level height determinations for the seven permanent tide gauge sites located in south-central Alaska from the NOAA data archives available over the world-wide web. These sites are: Anchorage, Seldovia, Cordova, Valdez, Seward, Nikiski, and Kodiak (St. Paul Harbor and Women's Bay). We also extracted records for three southeast Alaska sites (Sitka, Ketchikan, and Juneau) that are used to correct for local oceanographic effects as discussed below. The data were supplemented by paper records for the Seward tide gauge. From these monthly data we formed annual means from which we derived rates of apparent sea level change following the procedure outlined in *SP*91. The procedure corrects for local oceanographic and atmospheric effects based on the coherence between the residuals to the detrended tide gauge rates at the individual stations and the average residuals from detrended rates at the three southeast Alaska locales, a region well removed from 1964 rupture zone. The only significant difference between our procedure and that of *SP*91 is that we rejected any annual means that were derived from less than nine monthly means, whereas some of the annual means in *SP*91 were derived from less than six monthly values. Since there is a strong annual oscillation in the tide gauge readings, we sought to minimize the possibility that the analysis would be biased by sea-

sonal effects even if it meant some decimating the data set somewhat. Nevertheless, the apparent sea level rates we obtained by analyzing the data through 1988 closely reproduced the rates reported in *SP*91. We estimated uplift rates at each of the sites, by adding 2 mm/yr (to account for eustatic sea level change and postglacial rebound) to the negative of the apparent rate of sea level change, whereas, *SP*91 added 2.5 mm/yr to account for the same effects. Although the value of 2 mm/yr is somewhat arbitrary at the mm/yr level, we did not attribute any additional uncertainty in our rate estimates due to this choice. The site-specific aspects of the data record at each of the seven tide gauges are summarized in Table 1.

Constant and Time-Dependent Rate Analysis

Figure 2 shows the apparent sea level through 1998 for all 7 sites with each plot showing both the uncorrected and corrected sea level heights and the line derived from a linear regression on the corrected observations. The slope of each regression line, i.e. the apparent rate of sea level change is given in Table 2. The variance reduction achieved by the southeast Alaska sea level correction is 85, 80, 42, 47 and 82 percent at Cordova, Valdez, Seward, Seldovia, Anchorage, respectively, but nearly zero at Kodiak and Nikiski. Figure 3 shows the residuals to the linear fit at each of the seven locales. It is noteworthy that there are several correlated residuals (e.g. between 1996 and 1998), suggesting that the southeast sea level correction is not fully successful in removing all correlated sea level fluctuations. Of potentially great importance are the systematic residuals apparent at Kodiak and possibly Valdez and Cordova. The shape of these residuals suggests a time-dependence to the apparent sea level rate. We performed a least squares regression on the data using a quadratic (rather than linear) polynomial in time for each site except Nikiski and Anchorage (for which the data set is too sparse) and found that the rate change was formally above the corresponding uncertainty at Kodiak, Valdez, and Cordova, but was indistinguishable

from zero at Seward and Seldovia. The apparent sea level rates derived from the quadratic regressions are also summarized on Table 2. In Figure 4 we compare the linear and quadratic fits to the data. Since the errors in the tide gauge observations and monthly and annual means are not known, we estimated rate and rate change errors from the misfit of the regression curve to the data, as outlined in *Press et al.* [1986]. It is well known that error estimates obtained in this manor may underestimate the true error. The rate determinations from tide gauge observations are also subject to a variety of oceanographic noises that are not fully removed in the data processing. In addition it is well known that the GPS vertical data is subject to a variety of error, which are not yet fully understood. Thus we ascribe little physical significance to rate differences of a few mm/yr even when these differences exceed the reported error. Conversely, differences exceeding several mm/yr are likely to be significant provided the data set is sufficiently robust. Achieving such robustness in the tide gauge observations requires data sets spanning a decade or longer whereas the GPS measurements can achieve this consistency in several years.

Discussion and Interpretation

There are two important questions we wish to discuss in this section. The first is the whether there has been any change in the rate of crustal uplift since the 1964 earthquake. We will examine this question by taking a more critical look at the tide gauge data itself and then we will compare the tide gauge results with other geodetic data. The second question is how to interpret the observed motions in terms of the underlying tectonic processes of the region.

Apparent sea level change and crustal uplift rates

In previous studies there has been evidence both for and against time-dependent crustal deformation following the 1964 earthquake. *Brown et al.* [1977] and *Cohen* [*1998*] examined several leveling surveys and concluded that there was a time dependent decay over a period of several

years in the rate of crustal uplift along Turnagain Arm following the earthquake. In a series of papers [*Cohen et al.*, 1995, *Cohen*, 1996, *Cohen and Freymueller*, 1997] we have argued that the cumulative postseismic uplift through the late 1990s is consistent with a transient postseismic process as well. However, *SP*91 found some evidence for some change in the postseismic uplift rate as their tide-gauge data analyzed through 1988 produced slower rates when all the data was used than when data prior to 1973 was excluded. Since some of the rates they observed were much larger than the preseismic and interseismic averages, they speculated that a relaxation process occurring on a time scale of 10^2 might be operating. We [*Freymueller et al.*, [1999]) have recently argued that the unexpected trenchward horizontal motion of the western portions of the Kenai Peninsula might be due to continuing or delayed postseismic slip on deep portions of the plate boundary that lie below a region that is unlocked and not subject to much moment release during great earthquakes.

We will discuss the results at the individual sites starting at Cordova, the site located closest to the downdip end of the 1964 coseismic rupture, and progressing to other sites at increasing distance from the rupture edge. Where we cite GPS results, they are from an update (inclusion of data from 1998) of the analysis in *Freymueller et al.* [1999] (data through 1997).

At Cordova the rate of sea level change from the linear analysis is 6.7 ± 0.4 mm/yr. This compares to the *SP*91-determined rate of 9.7 ± 0.5 mm/yr. The nearly 1 cm/yr subsidence implied by the earlier estimate of sea level height change cannot be sustained over the entire earthquake recurrence interval of several hundred years; thus it is not entirely surprising that our data incorporating data for 10 years following the *SP*91 analysis shows a deceleration in the sea level height change. The quadratic regression analysis gives a rate change, 2c, in the sea height equation, $h = a + b\Delta t + c(\Delta t)^2$, where $\Delta t = 1998.5 - t$, of $2c = 0.39 \pm 0.06$ mm/yr^2. However, an

examination of the height residuals to the constant rate solution shows that most of the time dependent signal comes from the early and later epochs of the record. Thus we are somewhat skeptical as to whether the mathematically significant temporal variation in the uplift rate is physically real. Nevertheless, we must point out that even a qualitative evaluation of the corrected uplift rates shown in Figure 2 shows that there has been little if any change in apparent sea level height since the late 1980's. We applied the F test to determine whether the improvement in the residuals with the quadratic curve over the linear case is statistically significant. The improvement passes the F test [*Mikhail,* 1976] at the 1% level indicating that the 99% probability that the improvement is meaningful. The F statistic is *Zhao et al.*, 1995]

$$F = \frac{(SSR_1 - SSR_2)/(DF_1 - DF_2)}{(SSR_2)/(DF_2)} \tag{1}$$

where SSR is the sum of the squared residuals and DF is the number of data points minus the number of parameters. Recent GPS observations provide a weak argument against a rate change. The subsidence rate from the GPS data is -13.2 ± 7.1 mm/yr which is in better agreement with the average rate of -4.7 ± 0.4 mm/yr than the nearly zero rate of 1.8 ± 1.0 mm/yr predicted by the quadratic analysis for 1996.5. The GPS-derived rate has large error bars because it is based on only a few recent surveys. In addition, GPS vertical measurements are subject to a variety of errors that can increase the actual uncertainty well beyond the formal error estimates [*Mao et al.*, 1999]

At Valdez the data record dates back to 1975, 11 years after the Prince William Sound Earthquake. The rate of apparent sea level change since that time, -0.2 ± 0.7 mm/yr, is not significantly different from zero, but is less than the *SP*91 rate of 5.5 ± 0.9 mm/yr. There is a mathematically significant change in the sea level rate of 0.77 ± 0.14 mm/yr^2 that produces a

rapid transition from crustal subsidence to crustal uplift. The quadratic sea height solution passes the F test for an improvement over the linear solution and yields an estimate for the crustal uplift rate in 1996.5 that is a rapid 9.2 ± 1.6 mm/yr. Our qualitative assessment of the residuals in Figure 3 again makes us somewhat skeptical about ascribing a great deal of physical significance to the mathematical result particular in view of the residual offset between 1995 and 1996 is a correlated feature found in many of the plots However, GPS measurements that come from a site about 5 km away, do marginally confirm the recent uplift albeit with a large uncertainty. The GPS-derived uplift rate is 8.7 ± 8.2 mm/yr.

At Seward the apparent sea level change is -1.2 ± 0.7 mm/yr and the time dependence is insignificantly different from zero. The implied crustal uplift rate of 3.2 ± 0.7 mm/yr is slightly less than two GPS results. one, 7.6 ± 3.5 mm/yr, obtained from measurements since 1993 at the adjacent T19, and the other, 9.5 ± 2.7 mm/yr obtained from measurements begun in 1995 at the newly installed site UAMF, located at the pier of the University of Alaska Marine Facility in Seward.

At Kodiak the rate of apparent sea level change from the linear analysis is -14.5 ± 0.7 mm/yr; however, there appears to be a significant change in the rate of -0.66 ± 0.11 mm/yr^2. Several other lines of argument also suggest that the time dependence is real. First, an examination of the height residuals shows that the temporal variation is more extensive than in the previous cases, i.e., it appears to span almost the entire domain of the data set. The quadratic solution passes the F test with a 99% probability that the improvement over the linear fit is statistical significant. Furthermore, the rate that we derived from the data through 1998 is slightly lower than that derived by *SP*91 from the data through 1988, -17.5 ± 0.8 mm/yr. The crustal uplift rate we predict from the time-dependent change in apparent sea level (for 1996.5, see Table 2) is 7.4 mm/y which is

good agreement with the GPS observed value of 9.2 ± 1.6 mm/yr. These values are less than the 14.8 ± 7.2 mm/yr observed by Very Long Baseline Interferometry (VLBI) in the late 1980's and 1990 [*Ryan, et al.*, 1993], although the difference is not statistically significant. The sea level rate for the period (1985-1998) that the tide gauge has been located at Women's Bay is -8.1 ± 1.1 mm/yr, slower than the rate of -21.1 ± 1.4 mm/yr derived for the period from 1967 to 1981 when the gauge was at St. Paul Harbor. This adds further credence to the suggestion that the rate has changed, but raises the possibility that the rate change was associated with the change in observing location. However, as the comments in Table 1 indicate, there was a consistency check between the observations at the two sites so we have no substantive evidence to suggest that the rate change is an artifact of the relocation of the tide gauge. In fact, we consider the observed rate change at Kodiak to be the most likely candidate for an actual physical change in the speed of crustal uplift. From the time dependent crustal uplift rate at Kodiak of $r = 6.1 + 0.66\,(1998.5 - t)$ mm/yr, we estimate that the uplift rate there decreased to half its immediate postseismic rate in about 12 years. This is somewhat faster than the 3-6 year decay estimated in *Cohen* [1998] for an amalgamation of sites along Turnagain Arm, the eastern Kenai, and elsewhere and may reflect the somewhat different tectonic settings of the various sites.

The rate of sea level change at Seldovia is -9.3 ± 0.8 mm/yr in good agreement with *SP*91's rate of -7.2 ± 1.4 mm/yr. The rate change term, 0.16 ± 0.18 mm/yr^2, is not significant. There nearest GPS site is in Homer, about 25 km to the northeast. Although the GPS uplift rate at Homer of 18.7 ± 2.4 mm/yr confirms rapid uplift on the western side of the Kenai Peninsula, the distance between the two locales is to far to make a quantitative comparison of the two rates. We are currently installing a "permanent" GPS site at Seldovia.

At Anchorage we obtained a sea level rate of 0.8 ± 1.3 mm/yr, a result which is quite consistent with the *SP*91 result of 1.9 ± 1.9 mm/yr and suggests very little, if any vertical crustal movement at Anchorage. Our analysis was based on data beginning in 1984 since the early records are quite incomplete. However, there is a somewhat more robust set of monthly mean tidal heights. This data set goes back to 1965 but still is missing yearly heights for most of the 1970's and early 1980's. The tidal heights produces a rate of -0.7 ± 0.9 mm/yr, again suggesting little vertical movement. An enigma is the recent GPS result at site VAN DUSEN located only 8 km to the southwest of the tide gauge. The GPS measurements indicate a rapid crustal uplift of 16.1 ± 6.5 mm/yr. The rapid uplift suggested by the GPS data cannot be dismissed as a single site anomaly for the next nearest GPS site, 1000, located about 10 km southeast of the tide gauge, gives an uplift rate of 12.4 ± 5 mm/yr.

The apparent sea level rate at Nikiski was derived from mean tide heights rather than mean sea level and is -9.9 ± 0.8 mm/yr. Given the fact that no data was collected at Nikiski from 1979 to 1997, the fact that *SP*91 obtained a higher rate of -18.7 ± 1.7 mm/yr is probably not significant. The GPS crustal uplift rate has been determined by observations that were begun in 1993 and is 13.3 ± 3.2 mm/yr.

As we discussed above, a portion of the Kenai Peninsula and the Turnagain Arm region may have experienced postseismic relaxation with a characteristic time of a few years. That relaxation died off near Seward to the south, and perhaps near Anchorage to the north. To determine whether any similar short term relaxation influenced our estimates of changes in uplift rate, we recomputed the quadratic regression curves excluding data through 1973. None of the quadratic solutions were strongly effected by this perturbation. At Kodiak the rate change with the decimated

data set was -0.59 ± 0.16 mm/yr^2 which agrees very well with the rate change of -0.66 ± 0.11 mm/yr^2 derived from the entire data set. Similarly at Cordova, the post-1973 rate change is 0.33 ± 0.09 mm/yr^2 compared to the 1965-1998 rate change of 0.39 ± 0.11 mm/yr^2. At Valdez the data set begins in 1975, so it does not contain any observations from the first decade after the earthquake.

Physical Significance

We now turn to a discussion of the physical significance of the uplift rates implied by these apparent sea level data. Table 3 shows both the coseismic vertical motion [*Plafker,* 1971] and uplift rates deduced from the tide gauge observations. As previously shown in Figure 1, all of the sites, with the exception of Cordova, lie landward of that portion of the megathrust that slipped during the 1964 earthquake and thus experienced coseismic subsidence. Cordova lies over a portion of the slip plane and thus underwent uplift. To some extent the observed pattern of postseismic vertical motion mirrors the coseismic pattern with all the sites exhibiting uplift except, perhaps, Cordova. The strike of the offshore trench varies with locale, but is about N44W in the center of the figure. The dip angle of the interseismically locked plate boundary increases from a few degrees in the NE portion of the figure to 10 degrees at Kodiak [*Brocher, et al,* 1994; *Johnson et al.,* 1996]. The velocity of the Pacific Plate relative to North America [*Demets et al.*, 1994] is about 55 mm/yr in a direction N17W at Seward, with an obliquity of 25 degrees there and 59 mm/yr at N28W at Kodiak where there is less than 5 degrees obliquity. The eastern region tends to rupture in infrequent great earthquake with recurrence intervals of several hundred years, while the Kodiak Island region ruptures both in infrequent great earthquakes and more frequent (50-60 yrs) large earthquakes [*Nishenko and Jacob*, 1990; *Perez and Scholz,* 1997].

Given the considerable variation in trench orientation and slab dip in the region under study, we

have found it more instructive to plot the uplift data as a function of distance from the axis of maximum coseismic subsidence 1964 earthquake (as estimated by *Plafker* [1971]) than as a function of distance from the trench. This axis is of considerable interest in the interpretation of geodetic data for it lies directly over the downdip end of the rupture in a uniform slip, elastic dislocation model of the earthquake. Assuming that the coseismically ruptured and interseismically locked portions of the megathrust are the same, this axis also lies over the downdip end of the locked region. The data showing the interseismic vertical motions as a function of distance from the axis are plotted in Figure 5. Also shown in the figure are the results of an elastic dislocation [*Okada*, 1985, 1992] estimate of the rate of interseismic uplift, assuming representative parameters, i.e. a plate convergence rate of 55 mm/yr, dip angle of 5 deg, and locking depth of 5-25 km. We ignore the effects of the obliquity of the plate velocity vector relative to the trench normal. The tide gauge rates are mean values for the entire postseismic period except for Cordova, Valdez, and Kodiak where we show both the mean rate and the 1996.5 value. For all three of these sites the mean rate fits the elastic dislocation model better than the 1996.5 rate. At Kodiak the agreement of the average rate with the model must be viewed particularly cautiously, since it lies in a different tectonic segment of the plate boundary than the other sites considered here [*Pulpan and Frohlich*, 1985; *Lu and Wyss*, 1996]. However, an uplift rate of 16.5 mm/yr is sustainable at Kodiak because it give a net uplift of less than a meter for a large earthquake recurrence time of 50 yrs. If such a rate were sustained for the several hundred year interval thought to be appropriate for the great earthquakes to the east, then the uplift would be much too great to be relieved by coseismic subsidence. The results for Seward, shown in Figure 5 and Table 3, suggest that the observed crustal movement there is consistent with elastic strain accumulation. This argument is buttressed by the contemporary GPS measurements of *Cohen and Freymueller* [1997] and

Freymueller et al. [1999] that show that the pattern of horizontal deformation on the eastern side of the Kenai Peninsula, including Seward, are consistent with elastic strain accumulation. There may have been rapid transient uplift on the eastern side of the Kenai Peninsula and along Turnagain Arm in the decade or so following the 1964 event, but the spatial pattern of that uplift is such that it died out near Seward. The vertical motions at Cordova, Valdez, and Anchorage are also is reasonable agreement with the elastic model provided the average velocities are used for Cordova and Valdez. By contrast, the crustal uplifts at Nikiski and Seldovia are much faster than would be expected for elastic strain accumulation. Again the horizontal GPS measurements in *Freymueller et al.* [1999] show that there is an anomalously rapid (~2 cm/yr) southeast motion of sites throughout the western side of the Kenai Peninsula. *Freymueller et al.* [1999} speculated that the horizontal motion there results from tectonic conditions quite different from the locked megathrust conditions on the eastern side of Kenai Peninsula. They proposed a model with continuous forward slip on the shallow portion of the plate interface and transient postseismic slip on a more steeply dipping downdip segment. If we assume that Seldovia and Nikiski do in fact lie in a tectonically different environment than the other sites (as suggested by the small coseismic moment release in this region during the 1964 earthquake), then it is a simple matter to find a transient deep slip model than fits the observations there. For example, Figure 6 shows the dislocation theory results for slip on a plane dipping at 25 degrees between depths of 40 km [*Oleskevich et al.*, 1999] and 80 km. The geometry is a reasonable fit to the plate interface geometry found by *Doser et al.* [1999], but none of the parameters are uniquely constrained so we can claim only that the observations on the western side of the Kenai peninsula are consistent with deep transient slip. We do not claim this interpretation is the only possibility.

Conclusions

The tide gauge records in southcentral Alaska are a useful data set for studying the spatial and temporal distribution of vertical crustal motion subsequent to the great 1964 Prince William Sound Earthquake. This new examination of the records incorporates 10 years of observations since the last study and provides a comparison between these observations and recent GPS measurements. The longer data span has enabled us to search the record for time-dependent behavior and we find considerable evidence for a decrease in the rate of crustal uplift at Kodiak with a decay time on the order of a decade. We also find that the rapid uplift at Seldovia and Nikiski on the western side of the Kenai Peninsula has persisted for at least three and a half decades. There is a need for further observations at Cordova and Valdez, on the eastern side of the rupture, to determine whether the apparent rate of change at these sites is real. The data presented here are consistent with the idea that postseismic relaxation may be a multiphase process with the details dependent on both location relative to the coseismic rupture features and time since the earthquake occurrence.

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Table 1: Tide Gauge Sites

Site	Comment
Cordova	Record is among the most complete with significant temporal gaps only in the middle to late 1960's.
Valdez	No data prior to 1975, but from then on the record is fairly complete.
Seward	Some missing data, but the record extends over the entire postseismic interval.
Kodiak	The operational tide gauge was located at St. Paul Harbor until 1984, then was moved a few kilometers to Women's Bay. A leveling survey connects the two sites and the leveling result was verified by the simultaneous operation of tide gauges at both sites for two months in 1984. The tide gauge and leveling data agree in the offset to within 1.5 cm. Separate analyses of the St. Paul Harbor (1967 - 1982) and Women's Bay (1985-present) records reveal a substantially faster uplift rate when the gauge was located at St. Paul Harbor, than at Women's Bay.
Seldovia	Strong record with only a few missing data points. There is a significant anomaly in the late 1970's which is not removed by the correction procedures employed herein; however the subsequent record is well behaved.
Anchorage	Interpretation of the tide gauge signal at Anchorage is handicapped by two factors. First, as *Brown et al.* [1977] and SP91 point out Anchorage (and to a much lesser extent Seward) may exhibit a sinusoidal oscillation with a period of several years in the first decade following the earthquake. This oscillation is less obvious at Anchorage in our data set that ofSP91 because we have deleted the annual means that are based on less than 9 monthly means. Second, there are very few data available from the early 1970's until the mid 1980's. After that the record becomes more robust. An alternative sea level record has been derived from the more complete set of monthly mean tide data.
Nikiski	The tide gauge operated through much of the 1970's, then was reactivated in 1997.

Table 2: Rate of Apparent Sea Level Change, r - Most Recent to Oldest Determinations

Tide Gauge	Time Period	r, linear sea level analysis, (mm/yr)	r, quadratic sea level analysis, $r = b + 2c\Delta t$ b(mm/yr); 2c (mm/yr^2); $\Delta t = 1998.5 - t$	Ref.	Comment
Cordova	1965-98	6.7 ± 0.4	-0.6 ± 1.0 ; 0.39 ± 0.06	(1)	
	1974-88	9.4		(2)	
	1964-88	9.7 ± 0.5		(2)	
	1964-74	12.7 ± 2.4		(3)	
Valdez	1975-98	-0.2 ± 0.7	-8.7 ± 1.6 ; 0.77 ± 0.14	(1)	
	1974-88	5.5 ± 0.9		(2)	
Seward	1965-98	-1.2 ± 0.7	-2.7 ± 2.7 ; 0.09 ± 0.15	(1)	
	1974-88	2.9		(2)	
	1964-88	0.1 ± 1.0		(2)	
	1964-73	-11.3 ± 3.7		(3)	
Kodiak	1985-98	-8.1 ± 1.1		(1)	Women's Bay (WB)
	1967-98	-14.5 ± 0.7	-4.1 ± 2.1 ; -0.66 ± 0.11	(1)	WB and SP
	1974-88	-14.8		(2)	
	1967-98	-17.5 ± 0.8		(2)	
	1967-81	-21.1 ± 1.4		(1)	St. Paul Harbor (SP)
	1965-74	-86.8 ± 38.4		(3)	SP
Seldovia	1966-98	-9.3 ± 0.8	-11.8 ± 2.9 ; 0.16 ± 0.18	(1)	
	1974-88	-7.0		(2)	
	1964-88	-7.2 ± 1.4		(2)	
	1964-74	-28.1 ± 8.1		(3)	
Anchorage	1984-98 1965-98	0.8 ± 1.3 -0.7 ± 0.9		(1)	mean sea level mean tide level
	1964-88	1.9 ± 1.9		(2)	
	1964-74	-14.3 ± 7.6		(3)	
Nikiski	1972-98	-9.9 ± 0.8		(1)	no data from 1981 through 1996
	1971-79	-18.7 ± 1.7		(2)	no data after 1984

(1) This study; (2) *Savage and Plafker* [1991]; (3) *Brown et al.* [1977].

Table 3: Tide Gauge[1] and GPS Rates of Uplift

Tide Gauge Site (TGS)	TGS Mean Uplift Rate (mm/yr)	TGS 1996.5 Uplift Rate[2] (mm/yr)	GPS Site	GPS Uplift Rate (mm/yr)	comment
Cordova	-4.7 ± 0.4	1.8 ± 1.0	4050	-13.2 ± 7.1 [8]	GPS: **dates**
Valdez	2.2 ± 0.2	9.2 ± 1.6	POWE	8.7 ± 8.2 [8]	GPS: **dates**
Seward	3.2 ± 0.7		T19 UAMF	7.6 ± 3.5 [5] 9.5 ± 27 [5]	GPS: 1993-98 GPS: 1995-98
Kodiak[3]	16.5 ± 0.7	7.4 ± 2.1	KDK1 VLBI[6]	9.2 ± 1.6 [8] 14.8 ± 7.2	GPS: **dates** VLBI: 1984-90
Anchorage[4]	2.7 ± 0.9		VANDUSEN	16.1 ± 6.5 [5]	GPS: 1995-97
Nikiski	11.9 ± 0.8		NIK/NIK2	13.5 ± 3.2 [5]	GPS: 1993-98

1. Assumes combined effects of eustatic sea level rise and post-glacial rebound = 2 mm/y for the tide gauge-derived rates.
2. Cordova, Valdez, and Kodiak assumed to have time-dependent rate.
3. Combined Women's Bay and St. Paul Harbor.
4. Mean Tide Level Analysis.
5. Update of *Freymueller et al.* [1999] to include 1998 data.
6. VLBI measurement.
7. *Ryan et al.* [1993].
8. Previously unreported GPS data processed with update to *Freymueller et al.* [1999].

Figure Captions

Figure 1: Map of southcentral Alaska showing major cities, tide gauge locations (n.b. Nikiski is immediately northwest of Kenai), and coseismic uplift pattern for 1964 Prince William Sound Earthquake. From *Plafker* [1971].

Figure 2: Uncorrected (circles) and corrected (squares) annual sea level heights and linear least squares line with slope as given on Table 2.

Figure 3: Sea level height residuals (corrected sea level heights minus least squares line).

Figure 4: Corrected sea level heights and linear and quadratic least squares fits.

Figure 5: Uplift rate vs distance from axis of maximum coseismic subsidence (data points) and dislocation model for elastic deformation due to a locked megathrust (dashed line).

Figure 6: Uplift rate of western Kenai Peninsula sites (data points) and predicted uplift rate due to creep at depth in an elastic halfspace (solid line).

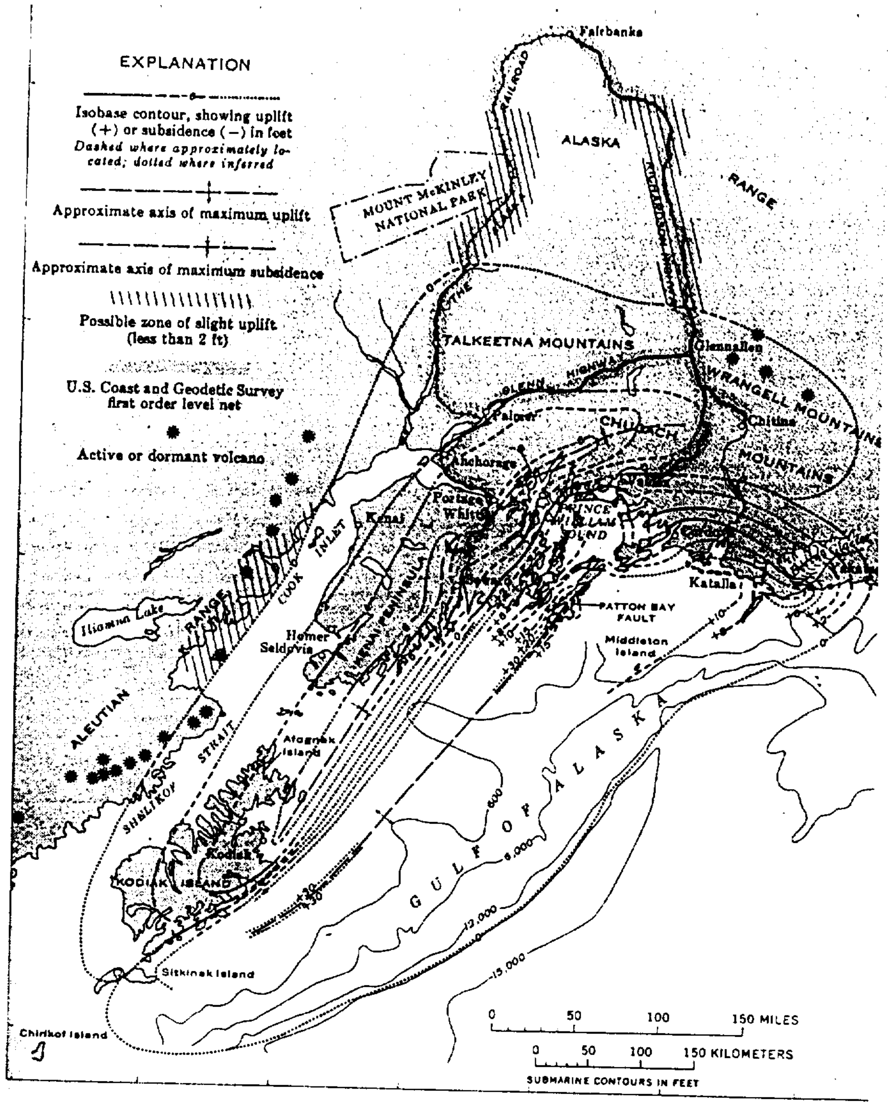

EXPLANATION
Isobase contour, showing uplift (+) or subsidence (−) in feet
Dashed where approximately located; dotted where inferred
Approximate axis of maximum uplift
Approximate axis of maximum subsidence
Possible zone of slight uplift (less than 2 ft)
U.S. Coast and Geodetic Survey first order level net
Active or dormant volcano
Fairbanks
ALASKA
RANGE
MOUNT McKINLEY NATIONAL PARK
TALKEETNA MOUNTAINS
Glennallen
WRANGELL MOUNTAINS
Chitina
CHUGACH MOUNTAINS
Palmer
Anchorage
Portage
Whittier
Kenai
COOK INLET
Iliamna Lake
ALEUTIAN RANGE
PRINCE WILLIAM SOUND
Katalla
PATTON BAY FAULT
Middleton Island
Homer
Seldovia
Afognak Island
SHELIKOF STRAIT
Kodiak
KODIAK ISLAND
Sitkinak Island
Chirikof Island
GULF OF ALASKA
0 50 100 150 MILES
0 50 100 150 KILOMETERS
SUBMARINE CONTOURS IN FEET

Figure 1

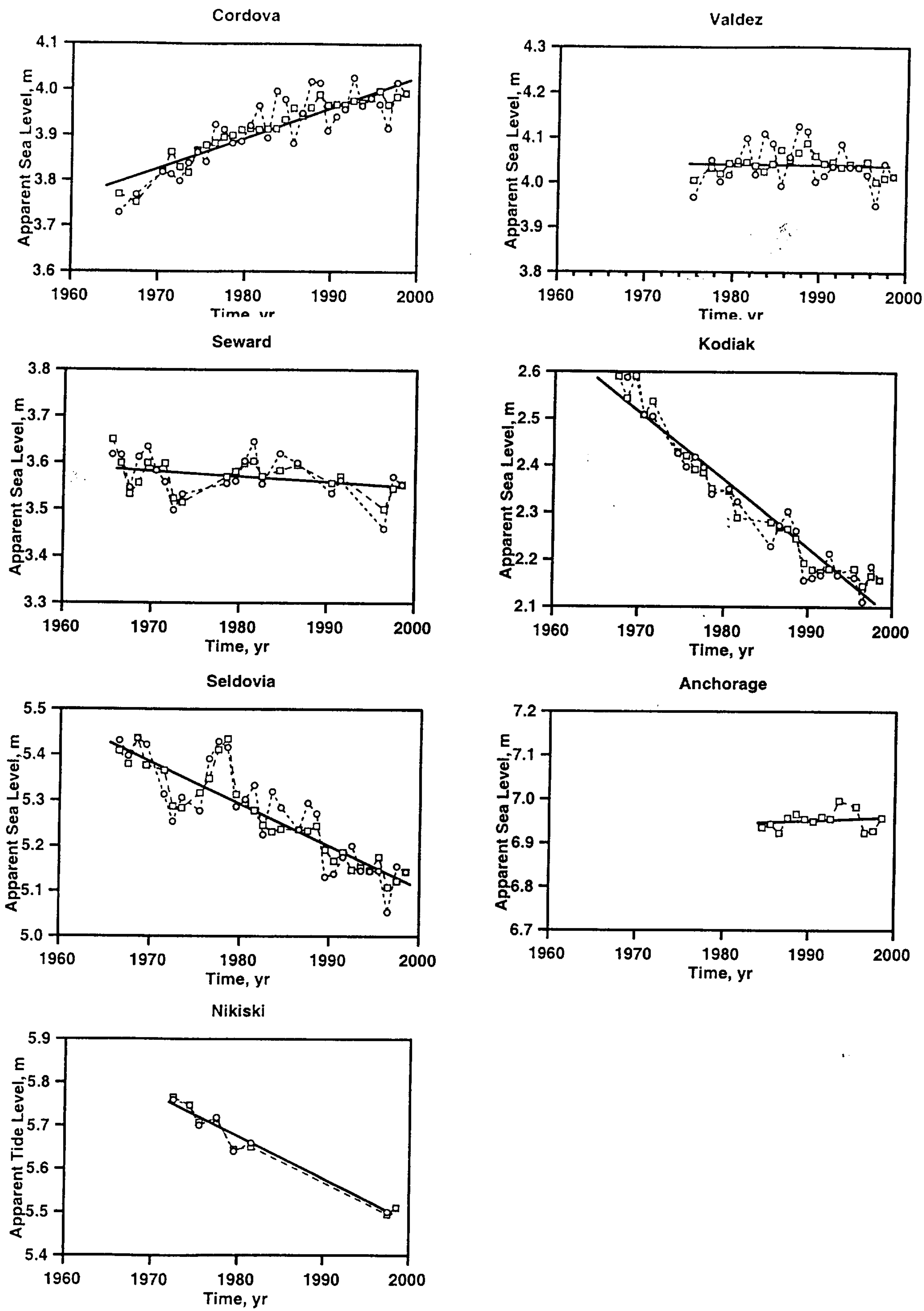
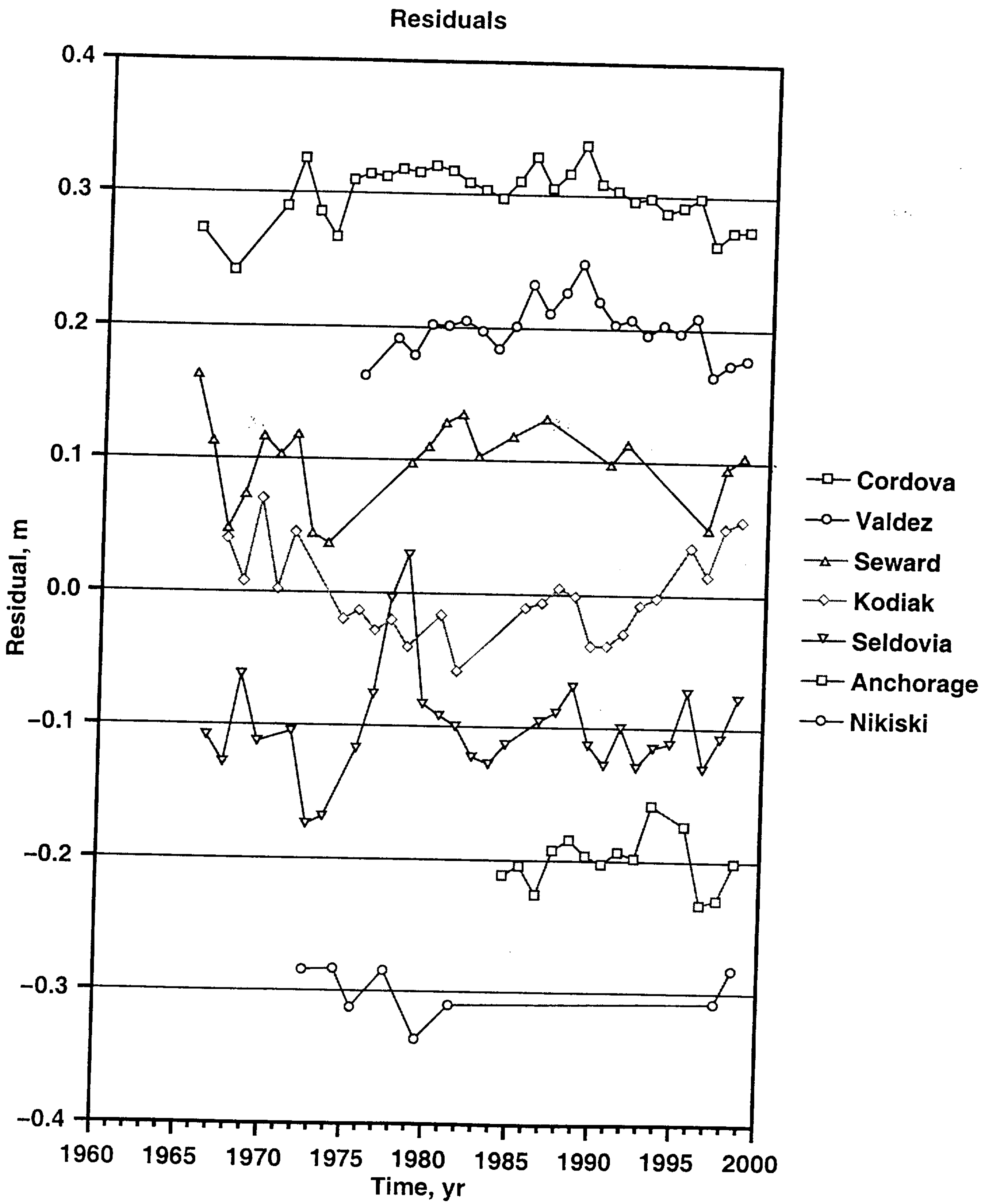
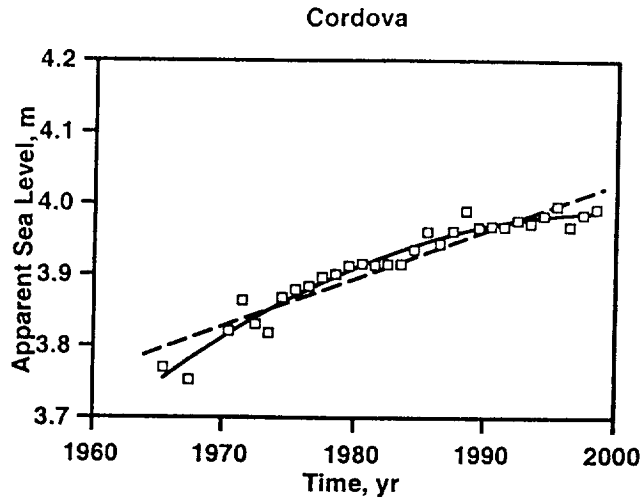

Cordova
Valdez
Seward
Kodiak
Seldovia
Anchorage
Nikiski
Apparent Sea Level, m
Apparent Tide Level, m
Time, yr

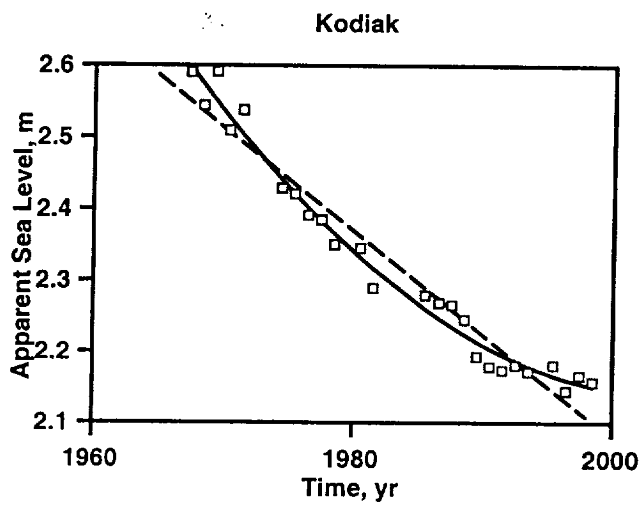
Figure 2



Residuals
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
Residual, m
1960
1965
1970
1975
1980
1985
1990
1995
2000
Time, yr
Cordova
Valdez
Seward
Kodiak
Seldovia
Anchorage
Nikiski

Figure 3


Cordova
4.2
4.1
4.0
3.9
3.8
3.7
Apparent Sea Level, m
1960
1970
1980
1990
2000
Time, yr


Kodiak
2.6
2.5
2.4
2.3
2.2
2.1
Apparent Sea Level, m
1960
1980
2000
Time, yr

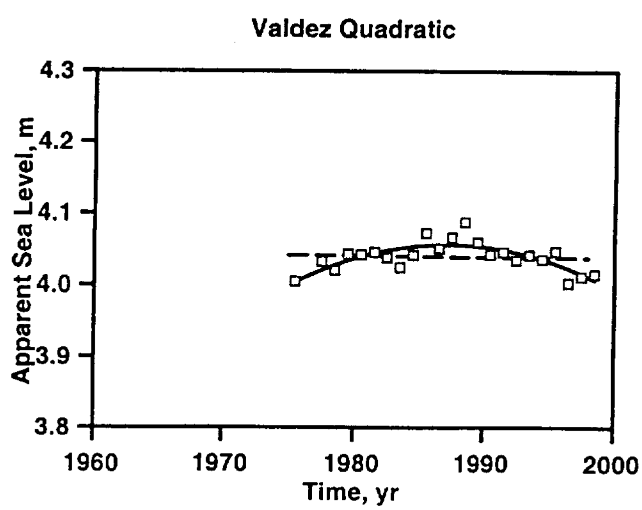
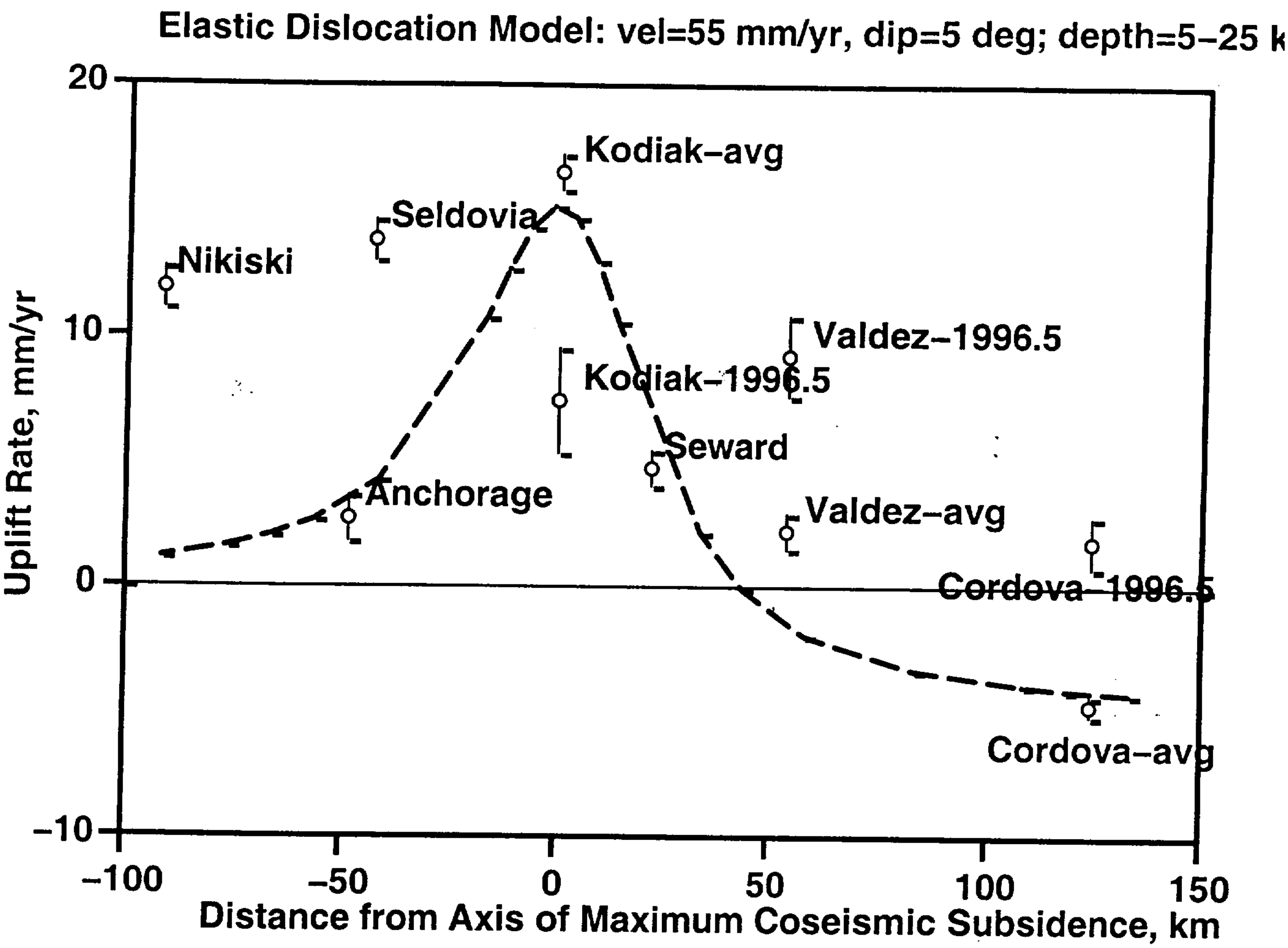
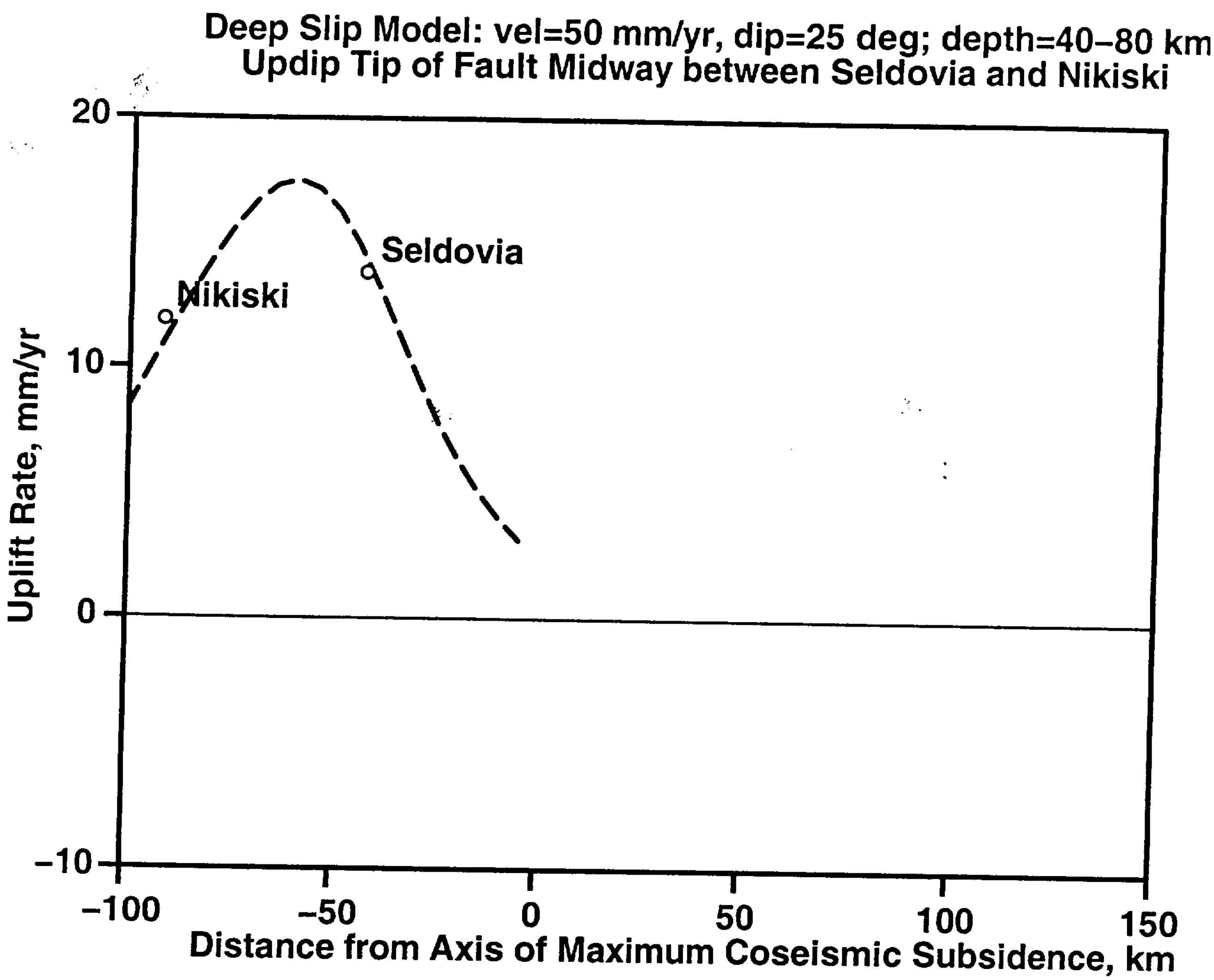

Valdez Quadratic
4.3
4.2
4.1
4.0
3.9
3.8
Apparent Sea Level, m
1960
1970
1980
1990
2000
Time, yr

Figure 4



Elastic Dislocation Model: vel=55 mm/yr, dip=5 deg; depth=5-25 k
Uplift Rate, mm/yr
20
10
0
-10
Kodiak-avg
Seldovia
Nikiski
Valdez-1996.5
Kodiak-1996.5
Seward
Anchorage
Valdez-avg
Cordova-1996.5
Cordova-avg
-100
-50
0
50
100
150
Distance from Axis of Maximum Coseismic Subsidence, km

Figure 5



Deep Slip Model: vel=50 mm/yr, dip=25 deg; depth=40–80 km
Updip Tip of Fault Midway between Seldovia and Nikiski
Uplift Rate, mm/yr
20
10
0
−10
Seldovia
Nikiski
−100
−50
0
50
100
150
Distance from Axis of Maximum Coseismic Subsidence, km

Figure 6